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Recognizing and dating prehistoric liquefaction features: Lessons learned in the New Madrid seismic zone, central United States

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Abstract. The New Madrid seismic zone (NMSZ), which experienced severe liquefaction during the great New Madrid, Missouri, earthquakes of 1811 and 1812 as well as during several prehistoric earthquakes, is a superb laboratory for the study of world-class, earthquake-induced liquefaction features and their use in paleoseismology. In seismically active regions like the NMSZ, frequent large earthquakes can produce a complex record of liquefaction events that is difficult to interpret. Lessons learned studying liquefaction features in the NMSZ may help to unravel the paleoseismic record in other seismically active regions. Soil characteristics of liquefaction features, as well as their structural and stratigraphic relations to Native American occupation horizons and other cultural features, can help to distinguish prehistoric liquefaction features from historic features. In addition, analyses of artifact assemblages and botanical content of cultural horizons can help to narrow the age ranges of liquefaction features. Future research should focus on methods for defining source areas and estimating magnitudes of prehistoric earthquakes from liquefaction features. Also, new methods for dating liquefaction features are needed.

Introduction

In eastern North America, where seismogenic faults are difficult to identify, earthquake-induced liquefaction features have been the focus of a number of paleoseismology studies [e.g., *Amick et al.*, 1990; *Obermeier et al.*, 1990; *Saucier*, 1991; *Tuttle and Seeber*, 1991; *Munson et al.*, 1992; *Obermeier et al.*, 1992; *Tuttle and Schweig*, 1995]. Several recent earthquakes, including the 1988 Saguenay event in Quebec and the 1989 Loma Prieta and 1994 Northridge events in California, induced liquefaction but were not associated with surface rupture [*Tuttle et al.*, 1990, 1993; *Plafker and Galloway*, 1989; *Hall*, 1994]. These earthquakes raised the awareness that certain types of prehistoric earthquakes could not be recognized by studying surface faults. Therefore liquefaction features are likely to be used increasingly in paleoseismology studies around the world, wherever sediments susceptible to liquefaction are present. Criteria for distinguishing earthquake-induced liquefaction features from other types of soft-sediment deformation structures already have been set forth in several papers [e.g., *Obermeier et al.*, 1990; *Tuttle et al.*, 1992; *Obermeier*, 1994; *Sims and Garvin*, 1995]. However, large uncertainties remain in the use of liquefaction features in paleoseismology. To advance the methodology, we must improve our ability to date liquefaction features and to interpret the size distribution of liquefaction features in terms of earthquake locations and magnitudes.

The New Madrid seismic zone (NMSZ) is one of the best regions in the United States to study liquefaction features and to advance the usefulness of liquefaction features in paleoseismology (Figure 1). In this region, where liquefaction has been induced by historic and prehistoric earthquakes, liquefaction features are abundant, widespread, and present in a variety of shapes, sizes, and ages. Many of the surficial vented deposits, or sand blows, are so large (commonly 1.0 to 1.5 m in thickness and 10 to 30 m in diameter) that they are still easy to identify on the ground surface and on aerial photographs and satellite images despite years of modification by plowing (Figure 2). Sand blows have been mapped over thousands of square kilometers [e.g., *Fuller*, 1912; *Saucier*, 1977; *Obermeier*, 1989]. Most of these features were thought to have formed during the New Madrid earthquakes of 1811 and 1812 [*Obermeirer*, 1989; *Wesnousky and Leffler*, 1992]. However, recent findings by *Li et al.* [1994] and *Tuttle and Schweig* [1995] indicate that many of these features are prehistoric in age. In this paper, we report on lessons learned about recognizing and dating prehistoric liquefaction features. This information should be useful to paleoseismologists conducting studies in the NMSZ and other regions where earthquakes induce liquefaction.

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Recognizing Prehistoric Liquefaction Features

In a seismically active region like the NMSZ, where several generations of liquefaction features may coexist, distinguishing between liquefaction events can be difficult. Where liquefied sand vented to the surface and most of its postdepositional soil horizon remains intact, prehistoric sand blows often can be distinguished from those that formed in 1811 and 1812 by their soil characteristics. The historic sand blows, which in the NMSZ are less than 200 years old, are characterized by 8- to

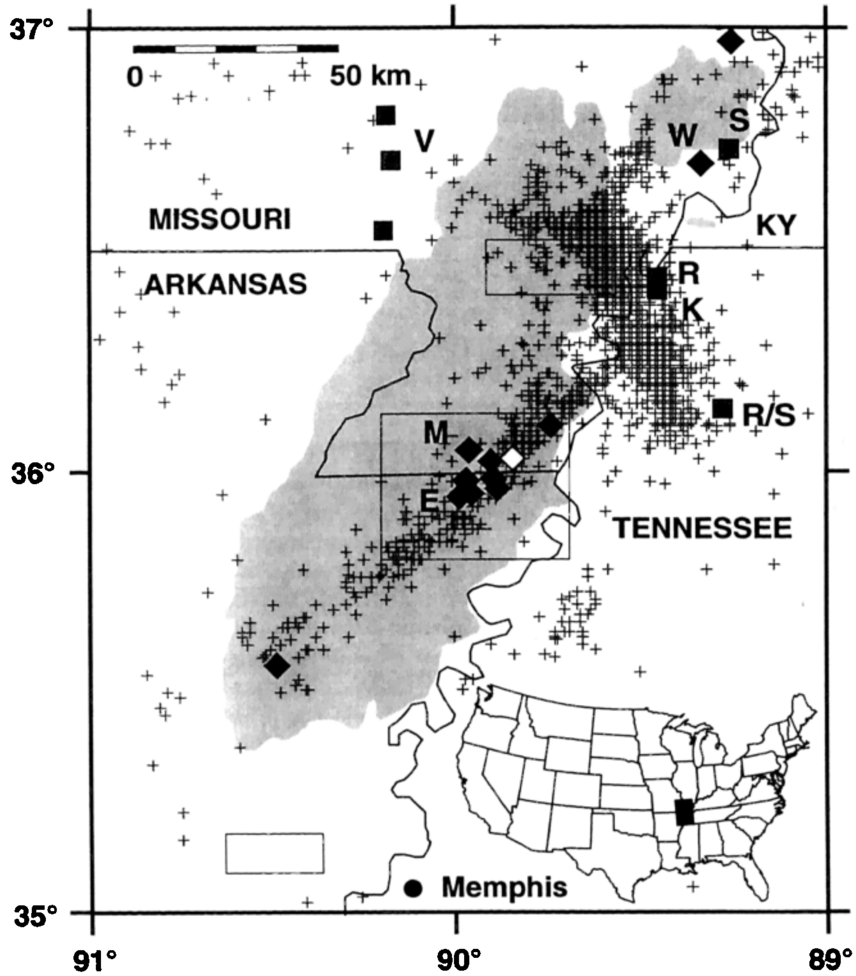

Figure 1. Map of the New Madrid seismic zone. Inset of a map of the conterminous U.S. shows location of study area. Seismicity (1974–1991) shown by crosses. Gray shading represents the area where >1% of the ground surface is covered by sand blow deposits [*Obermeier*, 1989]. From the paleoseismological study of *Tuttle and Schweig* [1995], locations of paleoliquefaction features denoted by solid diamonds; open diamond denotes location of historic liquefaction features. E, E-525, E-557, and E-560; M, M-1A and M-801; and W, W-102. Sites of other paleoseismological studies denoted by shaded squares and labeled R, *Russ* [1982]; K, *Kelson et al.* [1994]; R/S, sites of *Rodbell and Schweig* [1993]; S, *Saucier* [1991]; and V, *Vaughn* [1991]. Study areas of *Wesnousky and Leffler* [1992] are outlined by boxes.

10-cm-thick A horizons, single grain or massive structure, and loose consistence, whereas prehistoric sand blows are characterized by more advanced soil development, including thicker A horizons, angular or subangular blocky structure, and friable consistence. For example, at site E-560, a 32- to 35-cm-thick A horizon (including plow zone), characterized by angular blocky structure and friable consistence, has developed in sand blow A thought to have formed about A.D. 1300 ± 100 years (Table 1). Based on soil characteristics of different age sand blows, such as the sand blow given in the example above, A horizons appear to develop in sand at an average rate of 0.4–0.5 mm/yr in this region.

In the case of buried sand blows, the thickness of the paleo-A horizon is indicative of the amount of time the sand blow was exposed at the surface prior to burial. For example, at site W-102, a 35- to 37-cm-thick paleo-A horizon developed in the top of sand blow B thought to have formed prior to A.D. 1020 and later buried by sand blow A (Table 1 and Figure 3). Based on the thickness of its A horizon and assuming that the rate of soil development has remained constant during the past 1000 years, sand blow B was probably exposed at the surface for about 800 years prior to burial. The overlying sand blow, characterized by an 8- to 10-cm-thick paleo-A horizon, is overlain by overbank deposits of the Mississippi River. Therefore sand blow A was probably exposed about 200 years prior to burial. This site is located on an interfluve within the Holocene meander belt of the Mississippi River and has been subjected to overbank deposition. The buried sand blows at this site suggest that other liquefaction features may be preserved at depth below younger sand blows and below recent overbank deposits. Buried sand blows and other lequefaction features often are exposed in cutbanks of borrow pits, drainage ditches, and rivers in this region.

In the Mississippi River Valley, Native American culture thrived for 5000 years prior to the campaign of the Spanish explorer De Soto in the 1540s [*Morse and Morse*, 1983]. In this region, many archeological sites have been found in association with liquefaction features. M. P. Tuttle et al. (Use of archaeology to date liquefaction features and seismic events in the New Madrid seismic zone, central United States, submitted

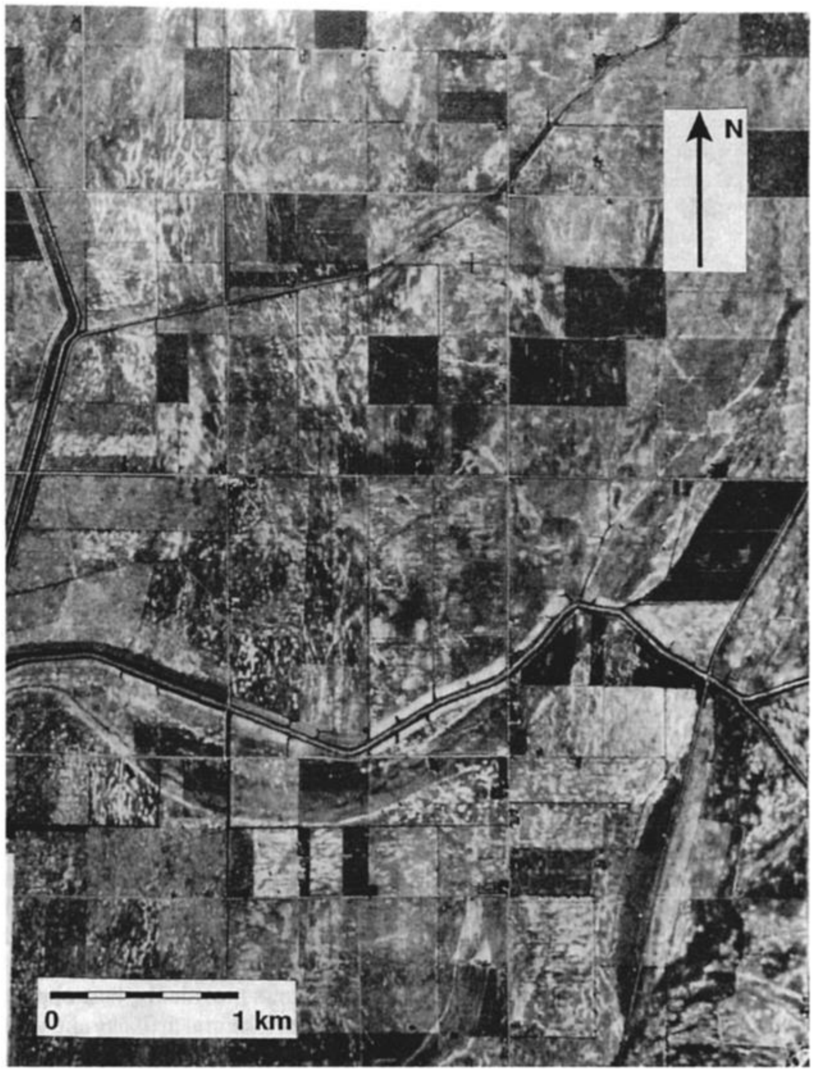

Figure 2. SPOT panchromatic digital image acquired January 13, 1987 (Ref. 1-598-277-870113-1655-27-1P), of southeastern Missouri showing the large size and prevalence of sand blows (light colored circular to elliptical features) and sand fissures (light colored linear features) in the NMSZ. North is toward the top of the photograph.

to *Geoarchaeology*, 1995; hereinafter referred to as M. P. Tuttle et al., submitted manuscript, 1995) hypothesize that sand blow deposits, which are relatively well-drained, were used preferentially by Native Americans as home, storage, and burial sites. Sand blows or sand dikes that are overlain or crosscut by Native American occupation horizons and other cultural features including fire pits and postmold casts must be prehistoric in age. For example, at site E-557 (Table 1 and Figure 4), an earthquake-related sand dike is overlain by an occupation horizon containing ceramic artifacts predominately of the Mississippian cultural period (A.D. 700 to 1670 (M. P. Tuttle et al., submitted manuscript, 1995). This sand dike therefore could not have formed during the 1811–1812 earthquake sequence but had to form either during or before the Mississippian cultural period.

Not every liquefaction feature will be a useful paleoseismic indicator. Sites must be found where relations indicate that the liquefaction features are prehistoric in age and materials are present for dating of the features. For these reasons, prehistoric liquefaction features should be sought in areas where Native American occupation horizons are likely to occur, specifically on relatively high land surfaces where soils are better drained. Previous searches by us and other investigators were conducted along drainage ditches that commonly were excavated along natural streams and bayous. These low-lying areas, characterized by clayey and poorly drained soils, were apparently unappealing home sites for Native Americans.

Dating Prehistoric Liquefaction Features and Events

In regions where earthquakes frequently induce liquefaction, distinguishing between closely timed liquefaction events can be a significant problem. If liquefaction features are to be correlated across a region and used to estimate source areas and magnitudes of prehistoric events, it is critical that the ages of the liquefaction features be well-constrained. Events separated by only a few hundred years are difficult to resolve using radiocarbon dating, the most commonly used method for dating liquefaction features. Radiocarbon ages are expressed as

Table 1. Age Constraints and Dates of Liquefaction Features

Site	Feature	Sample[a]	Conventional[b] Radiocarbon Ages, (years B.P.)	Calibrated[c] Radiocarbon Ages	Age Estimates From Ceramics and Artifacts	Maximum Age Range
W-102	sand blow A	W1	240 ± 60	<A.D. 1510–1600	not available	
				1620–1700		
				1720–1820		A.D. 770–1811
				1850–1860		
				1920–1950		
		S1	1140 ± 60	>A.D. 770–1020		
W102	sand blow B	S1	1140 ± 60	<A.D. 770–1020	not available	<A.D. 1020
E-525	sand blow	W6	170 ± 60	<A.D. 1650–1950	>200 B.C. to A.D. 200	A.D. 1180–1630
		W2	450±60	<A.D.1410–1530		
				1560–1630		
		S14	740 ± 70	>A.D. 1180–1400		
E-557	sand dike	W2	460 ± 60	<A.D. 1400–1520	~A.D. 700–1670	
				1570–1630		A.D. 1000–1420
		W4	660 ± 60	<A.D. 1270–1420	>A.D. 1000–1050 (botanicals)	
E-560	sand blow A	W1	300 ± 60	<A.D. 1460–1680	<A.D. 1400	
				1770–1800	>A.D. 800	A.D. 800–1400
				1940–1950		

[a]Wood (W) and soil (S) samples collected in association with liquefaction features. Sample locations shown on trench logs.
[b]Beta Analytic and Geochron radiocarbon laboratories determined ^{14}C ages which are based on a Libby half-life (5568 years) and adjusted for total isotope effects with measured ^{13}C values.
[c]Calibrated ages are in calendar years and reflect two sigma ranges determined by the Pretoria procedure [*Vogel et al.*, 1993]. In the context of this table, the < and > mean that the liquefaction feature formed earlier than or later than the given dates, respectively.

probability distribution functions often with standard deviations of 50 to 100 years. When radiocarbon ages are converted to dates in calendar years, even precise ages broaden into ranges of 200–400 years. This is due to fluctuations in ^{14}C in the atmosphere and uncertainties in the dendro-calibration curve [*Stuiver and Reimer*, 1993]. It is especially difficult to resolve the timing of events during the past 500 years, an important time period in seismically active regions. Age estimates of liquefaction features can be improved by carefully studying their soil characteristics and structural and stratigraphic relations, as well as the artifact assemblages and botanical content of cultural features associated with the liquefaction features (M. P. Tuttle et al., submitted manuscript, 1995). In this manner, the ages of liquefaction features can be estimated in several different ways. In addition, understanding of the context of samples collected for radiocarbon dating is enhanced. This approach involves detailed investigations at selected sites.

Sand blows provide the best opportunity for dating liquefaction events. Cultural artifacts and organic material within a soil horizon developed in or above the surface of the vented deposit can provide a minimum age of the event. Similar materials within a soil horizon buried by a sand blow can provide estimates of the approximate, or at least the maximum, age of

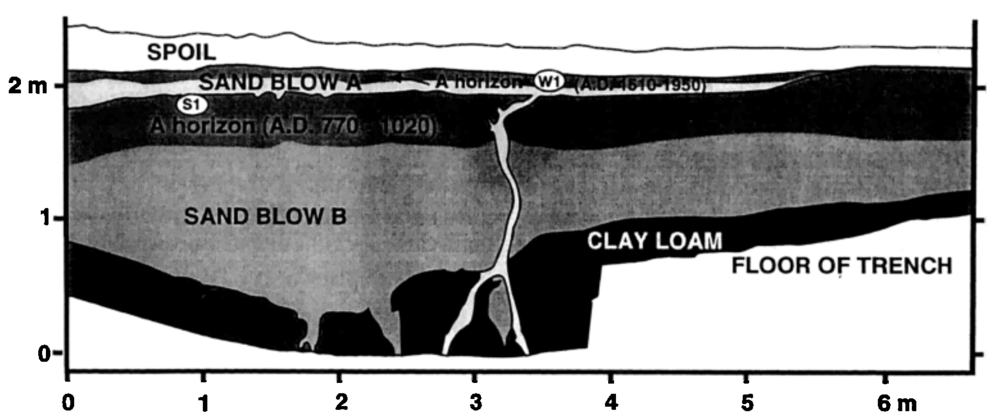

Figure 3. Log of exposure at site W-102 in southeastern Missouri (W on Figure 1). After *Li et al.* [1994]. Two sand blows and their associated feeder dikes are exposed and overlain by Holocene overbank deposits of the Mississippi River (covered by spoil in log). Feeder dike of sand blow A crosscuts sand blow B. Radiocarbon dating of a soil sample from the paleo-A horizon of sand blow B suggests that it formed prior to A.D. 1020 and radiocarbon dating of charred material from the paleo-A horizon of sand blow A provides a minimum age of that feature (Table 1). The thick paleo-A horizon of sand blow B suggests that it was exposed at the surface for ~800 years prior to burial, whereas the relatively thin paleo-A horizon of sand blow A suggests that it was exposed for ~200 years prior to burial.

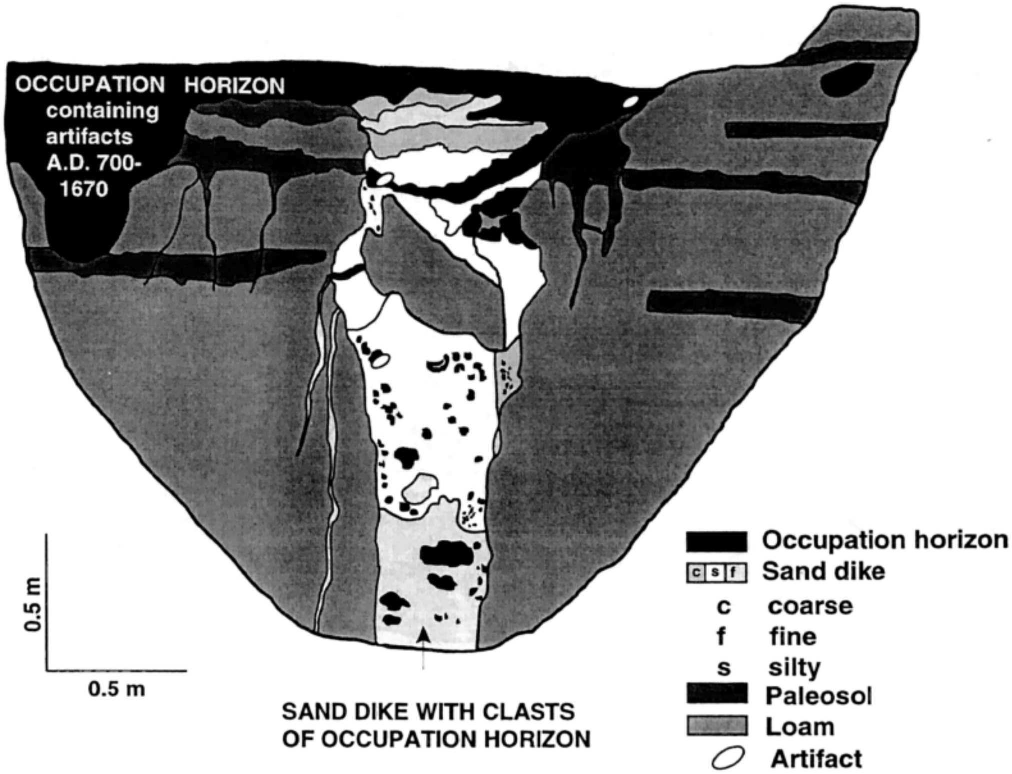

Figure 4. Log of trench wall at site E-557. A large sand dike disrupts one Native American occupation horizon and is overlain by a second occupation horizon, indicating that the dike must be prehistoric in age. A comparison of ceramic artifacts and plant remains from the different occupation horizons indicates that the sand dike formed during the Mississippian cultural period and after A.D. 1000 to 1050. Radiocarbon dating indicates that the sand dike formed prior to A.D. 1500.

an event. For example, at site E-525 (Table 1 and Figure 5), a tree root (W2 on Figure 5) that grew through the sand blow and along the top of the buried Native American occupation horizon yielded a carbon 13 adjusted radiocarbon age of 450 ± 60 years B.P. In addition, charred wood (W6) from a unit, interpreted as fill of a tree-fall crater, overlying the sand blow yielded an adjusted age of 170 ± 60 years B.P.

Below the sand blow, a soil sample (S14) collected from the top of the buried occupation horizon yielded a carbon 13 adjusted radiocarbon age of 740 ± 70 years B.P. This result reflects the mean residence time of carbon within the soil sample and provides a maximum age for the sand blow. Although soil samples can yield erroneous results due to contamination by both young and old carbon, the date of the sample from the top of the buried occupation horizon seems reasonable in this case. Because it was collected from the upper few centimeters of the occupation horizon, where a high percentage of the organic matter would have accumulated just prior to burial, the soil sample probably is fairly close in age to the formation of the sand blow. In addition, ceramic artifacts of the Middle Woodland cultural period (200 B.C. to A.D. 200 (M. P. Tuttle et al., submitted manuscript, 1995) are present within the buried occupation horizon and indicate that the sand blow formed in the past 2200 years. After calibration using the Pretoria procedure [*Vogel et al.*, 1993], the radiocarbon ages of the samples that predate and postdate the sand blow indicate that the liquefaction event occurred between A.D. 1180 and 1630.

It can be even more difficult to bracket the ages of the liquefaction events in those circumstances where sand-bearing water intruded overlying sediment, forming sand dikes and sills, but did not vent to the ground surface. In these cases, only the maximum age of liquefaction features can be determined based on the uppermost stratigraphic unit that they crosscut. For example, at M-1A (Table 1 and Figure 6), two generations of liquefaction features exposed in a ditch cutbank intruded Holocene meander-belt deposits of the Mississippi River. The uppermost unit intruded by the dikes is a mottled, reddish brown, clayey deposit. Radiocarbon dating of this unit would help to establish a maximum age for the two features. However, both features could be considerably younger than the deposit. Both crosscutting relations and soil characteristics of the two features indicate that dike A is younger than dike B and that they formed during different events. Because dike A exhibits almost no soil development, it may have formed during the 1811–1812 earthquake sequence. This example also demonstrates that recurrent liquefaction can lead to the intrusion of multiple generations of dikes.

Conclusions and Future Directions

Distinguishing between historic and prehistoric liquefaction features and dating closely timed liquefaction events in seismically active regions like the NMSZ present significant challenges for paleoseismologists. It is clear that a multidisciplinary approach utilizing archeology, geology, and pedology can help to address these problems. Soil and cultural horizons can be especially useful in distinguishing prehistoric from historic liq-

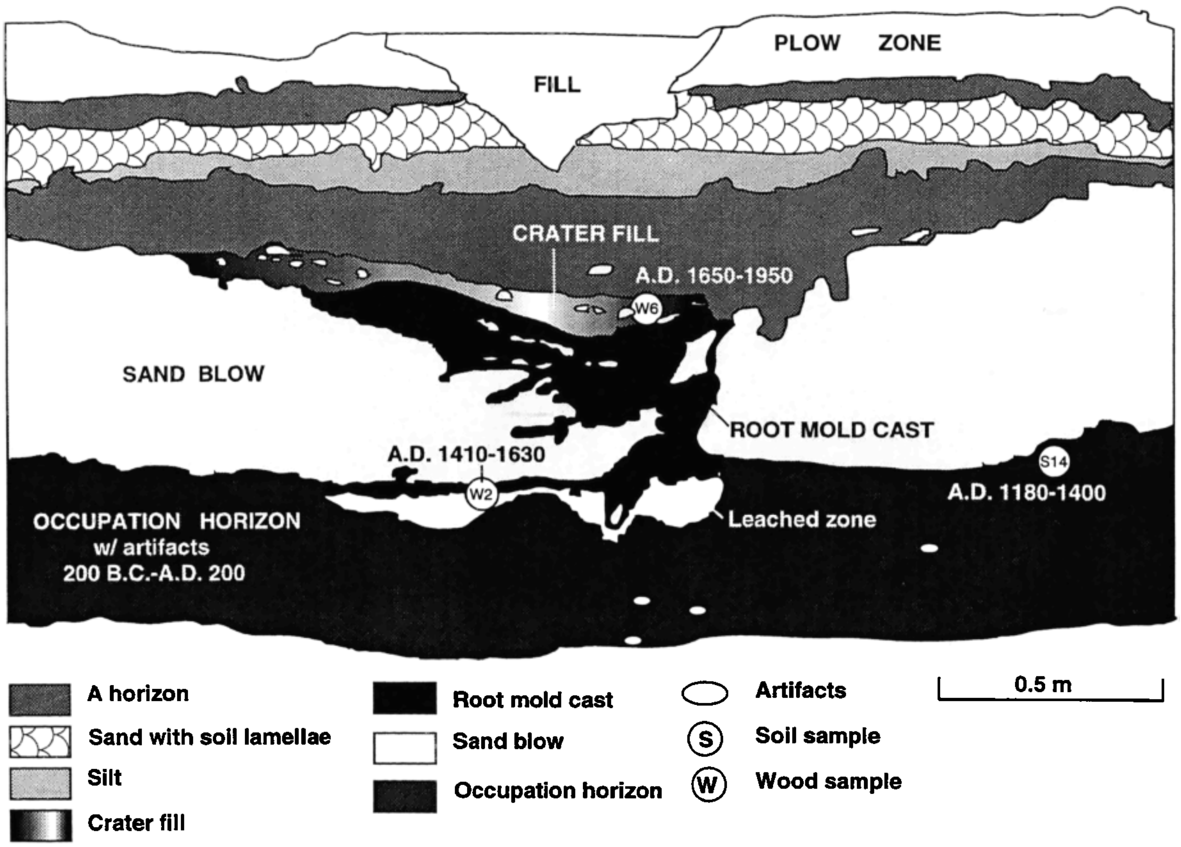

Figure 5. Log of trench wall at E-525 in northeastern Arkansas (E on Figure 1). The age of the sand blow at this site is constrained between A.D. 1180 and 1630 by radiocarbon dating of the organic-rich occupation horizon buried by the sand blow and of charred material within the root mold cast.

uefaction features. In the NMSZ, sand blows overlain by Native American occupation horizons or moderately thick soil horizons are prehistoric in age. If liquefaction features are to be correlated across a region and used to estimate the recurrence intervals, source areas, and magnitudes of earthquakes, it is important that the ages of the liquefaction features be well-constrained. The structural relations and soil properties of liquefaction features provide a measure of their relative ages. Radiocarbon dating of organic material associated with the liquefaction features provide maximum and minimum ages of the features. Given the standard deviations of radiocarbon ages and fluctuations in ^{14}C in the atmosphere, however, it can be difficult to narrowly bracket the ages of liquefaction features and thus to distinguish closely timed events. Analyses of artifact assemblages and botanical content of occupation horizons and other cultural features can help in this regard. Nevertheless, additional methods that can improve dating of liquefaction features are needed.

A soil development index might be useful for dating liquefaction features. Except for time, soil-forming factors (climate, living organisms, parent material, and topography) acting on sand blows in a given region rarely vary significantly over a period of a few thousand years. Therefore soil development within sand blows reflects the amount of time they have been subjected to soil-forming processes. Thermoluminescence is another method that may be useful for dating liquefaction features. Sand blows in the NMSZ whose ages are fairly well-constrained provide the opportunity to test the applicability of thermoluminescence dating in this context.

The size distribution of liquefaction features can be used to define the earthquake source areas and to estimate the magnitudes of prehistoric earthquakes. However, this is not a simple and straightforward process. As has been demonstrated by several recent earthquakes (e.g., 1988 Saguenay, Quebec, 1989 Loma Prieta, California, and 1994 Northridge, California), the distribution of liquefaction features can be irregular and not necessarily centered around the earthquake epicenter [*Tuttle et al.*, 1992; *Plafker and Galloway*, 1989; *Hall*, 1994]. This is probably due to a combination of factors including the characteristics of the earthquakes themselves, directivity and Moho reflections of seismic waves, and site conditions including the susceptibility of sediments to liquefaction. Given that most of these factors are unknown, there are large uncertainties associated with estimating the source areas and magnitudes of prehistoric earthquakes from liquefaction features. Experience gained from instrumentally recorded local earthquakes may suggest ways in which seismological factors can be taken into account when interpreting the distribution of prehistoric liquefaction features. In addition, the liquefaction susceptibility of deposits should be considered when using liquefaction features to define the source areas of prehistoric events.

Currently, magnitude estimates of prehistoric earthquakes are based on empirical relationships developed primarily from liquefaction events in interplate regions including California and Japan. As demonstrated by *Youd et al.* [1989] and *Law* [1990], these relationships may not be suitable for intraplate regions. Data that can be gathered from historic cases of earthquake-induced liquefaction (e.g., the 1811 and 1812 New Mad-

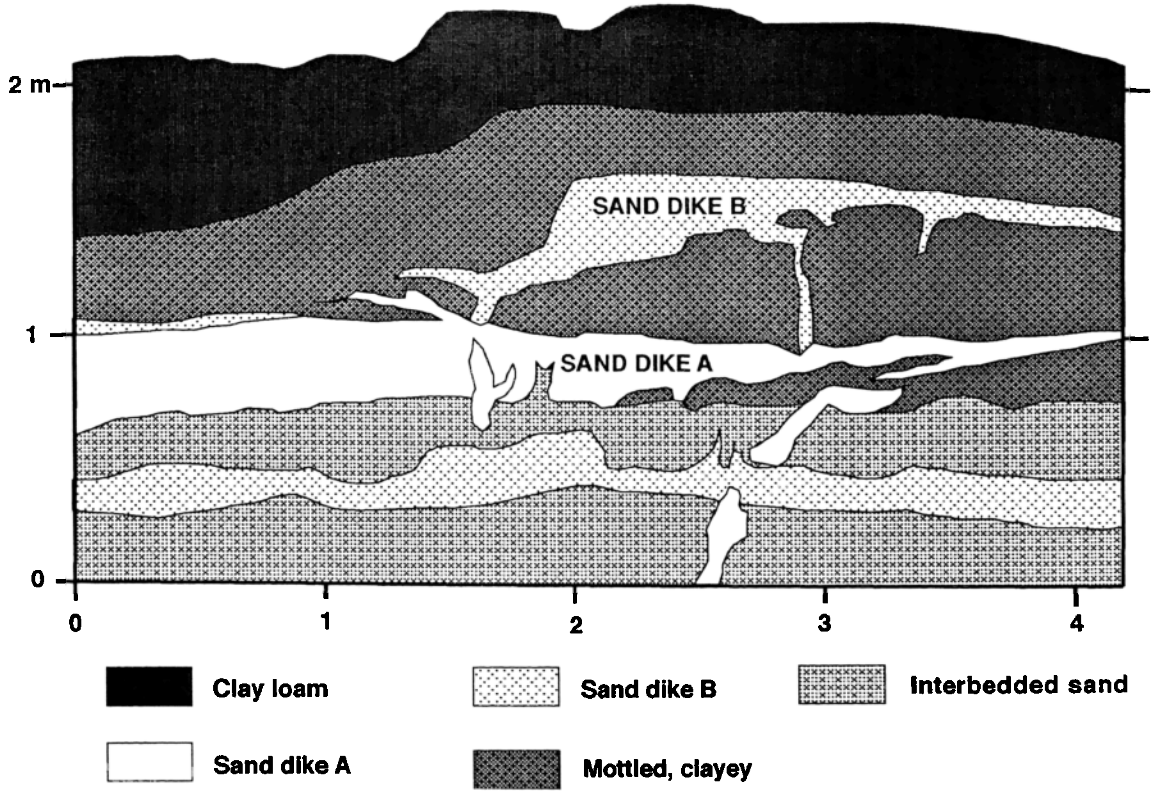

Figure 6. Log of ditch exposure at M-1A in southeastern Missouri (M on Figure 1). Two generations of liquefaction features intrude Holocene meander-belt deposits of the Mississippi River. It is difficult to date these features because they are not related to deposits vented to the ground surface. A maximum age for the sand dikes could be established by dating the uppermost unit that they intrude. Crosscutting relations and soil characteristics indicate that they formed during different events.

rid and 1895 Charleston, Missouri, events and the 1886 Charleston, South Carolina, event) and especially from modern cases of liquefaction where the characteristics of the earthquakes are well understood (e.g., the 1988 Saguenay, Quebec, event), are needed to calibrate these relationships for intraplate regions. As more data become available in intraplate regions, empirical relationships between earthquake magnitudes and the distances and effects of liquefaction will be better constrained, and therefore estimates of magnitudes and source areas of prehistoric earthquakes based on liquefaction features will be more realistic.

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